Transportation Research Part D 62 (2018) 268–282

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Comprehensive analysis of GHG emission mitigation potentials from technology policy options in South Korea's transportation sector using a bottom-up energy system model

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ARTICLE INFO

Keywords:
GHG emission
Mitigation potential
Energy system model
Technology policy

ABSTRACT

The South Korean government released a greenhouse gas (GHG) emission mitigation target for 2030 under the 2015 Paris Agreement and developed a detailed implementation plan in 2016 to achieve the target. In this study, we analyzed the GHG emission reduction potential of South Korea's transportation sector under the implementation plan. We first identified six technology policy options already adopted or being considered for adoption by the Korean government in the near future. Next, we quantitatively analyzed the GHG emission mitigation potential of each option, as well as the combination of all the options, via the best-known and most widely used bottom-up energy system model. In addition, we estimated the marginal mitigation costs of the options and their combination. We found that more than 30% of GHG emissions can be reduced compared to the business-as-usual scenario by adopting technology options, and that most reductions can be achieved by the road transportation subsector. We also showed that a comprehensive analysis is required to estimate the total potential of the entire transportation sector, because some duplication effects exist between the options. Lastly, based on the comprehensive analysis results, we provide four implications of the plan for climate change and transportation policy makers.

1. Introduction

Climate change related issues, including global warming and extreme weather events, are considered by many as one of the biggest challenges facing the world today. On December 12, 2015, nearly 200 countries at the United Nations Framework Convention on Climate Change (UNFCCC) agreed to adopt the Paris Agreement, a legally binding framework for an internationally coordinated effort to prevent climate change beyond 2020. In the Paris agreement, the UNFCCC established a global warming target of well below 2 °C of pre-industrial averages and defined a universal framework to enhance the global response to meet that target (UNFCCC, 2015). The Paris Agreement emphasizes processes rather than establishing mitigation targets and requires that each country prepares, communicates, and maintains successive nationally determined contributions (NDCs). NDCs are voluntary commitments from participating countries to pursue actions, policies, and regulations necessary to accomplish targets to mitigate greenhouse gas (GHG) emissions and to adapt to a changing climate.

Prior to the Paris Agreement, about 150 countries submitted "intended" NDCs (INDCs), which became the first NDCs under the

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https://doi.org/10.1016/j.trd.2018.03.007

Available online 13 March 2018
1361-9209/

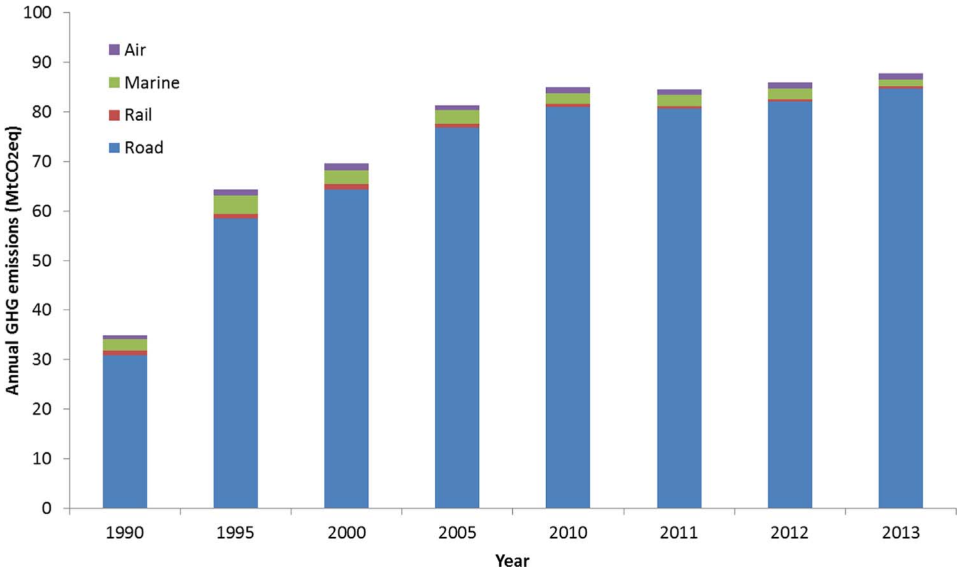

Fig. 1. Historical data of annual GHG emissions from South Korea's transportation sector.

Paris Agreement. In June 2015, the South Korean government also released an INDC, in which the government pledged to reduce GHG emissions to 37% below the business-as-usual (BAU) level of 850.6 Mt CO_2eq. by 2030 across all economic sectors (ROK Government, 2015a). The target includes an actual mitigation of 25.7% and an additional decrease through international market mechanisms equivalent to 11.3%. After the announcement, many domestic experts suggested that this target could only be achieved by taking very aggressive actions. South Korea is among the world's top 10 carbon emitters. As of 2013, the nation's total annual GHG emission was approximately 694.5 Mt CO_2eq (GIR, 2015). Considering the country's international responsibility and leadership in responding to climate change, the government has decided to commit to meeting its target by 2030.

After the Paris Agreement, the South Korean government developed a road map for achieving the target on time. To establish the plan, the government first segmented the sources of GHG emissions into eight sectors, including electricity, industry, commercial and residential, transportation, and agriculture. The government then analyzed GHG emission mitigation levels, potentials, and strategies considering the existing national policies and socioeconomic and technical changes in each sector. In December 2016, after combining the analysis results for all sectors based on the bottom-up approach, the government published a basic national plan for POST-2020 (ROK Government, 2016).

This study discusses how GHG emission mitigation potentials in South Korea's transportation sector for the plan were analyzed. As of 2013, the transportation sector was the fourth largest GHG emitter and accounted for about 12.7% of the nation's total annual GHG emissions (88.3 Mt CO_2eq). The average annual growth rate (compound annual growth rate, CAGR) of GHG emissions from this sector was 4.1% from 1990 to 2013, and the share from the road transportation sub-sector in GHG emissions has been 95% for the last 24 years (GIR, 2015) (Fig. 1).

For this study, we had three objectives: (1) to identify technology policy options that can be incorporated into the government's implementation plan for the transportation sector; (2) to quantitatively analyze the GHG emission mitigation potential of each option as well as the combinations of these options; and (3) to provide the implications of the plan to climate change and transportation policy makers. In order to analyze the GHG mitigation potential, we used the bottom-up energy system model, TIMES (The Integrated MARKAL-EFOM System), which is the most widely used and best-known optimization-based model and was created by the International Energy Agency's Energy Technology Systems Analysis Program (IEA-ETSAP) (Loulou et al., 2016). Even though there are other energy system models and methodologies to analyze GHG emission mitigation potential, we chose the TIMES model for future coordination with the results of the INDC, which were analyzed using the same model and released in 2015. In addition, the marginal mitigation costs of options were estimated and compared.

The remainder of this work is organized as follows: Section 2 reviews previous literature on GHG emission mitigation potential analysis for the transportation sector. Section 3 describes the model construction and the development of a baseline scenario. Section 4 introduces the details of these technology policy options we identified and the implementation of the options in the model. Section 5 provides the analysis results for each option and for the entire sector. Lastly, Section 6 presents our conclusions.

2. Literature review

Research on GHG emission mitigation potential for the transportation sector started in the mid-2000s when the Kyoto Protocol entered into force. Many studies used commercial bottom-up energy system models for this research. Ichinohe and Endo (2006) identified the most-effective mix of vehicles in the passenger car sector in Japan for reducing CO_2 emissions by using the MARKAL (MARKet ALlocation) model, a predecessor of the TIMES model that was also created by the IEA-ETSAP. Yeh et al. (2008) determined

the optimal mitigation strategies for the U.S. light-duty transportation sector by using the MARKAL model. Yan and Crookes (2009) analyzed the future trends of GHG emissions and energy demand in China's road transportation sector and assessed the effectiveness of possible mitigation options based on the Long-range Energy Alternatives Planning System (LEAP) model, a well-known accounting-based energy system model. He and Chen (2013) addressed possible policy measures to reduce energy consumption and to mitigate GHG emissions from China's road transportation sector by using the LEAP model. Hong et al. (2016) analyzed the relative contribution of the Korean road transportation sector to the national GHG emission reduction target by using the LEAP model. In addition, Kim et al. (2014) investigated the mathematical properties and constraints of bottom-up energy system models for analyzing GHG mitigation in the transportation sector.

In other studies, researchers developed their own methodologies to investigate the mitigation potential of GHG emissions from the transportation sector, and most of these researchers developed simple calculation-based accounting models. Zanni and Bristow (2010) analyzed historical and projected CO_2 emissions from road freight transportation in London and explored the mitigation potential from policies and logistics solutions. Ou et al. (2010) performed scenario analysis on the future trends of both direct and life-cycle GHG emissions in China's road transportation sector and assessed the effectiveness of possible mitigation options, including the use of alternative fuels and vehicles. Bueno (2012) explored six different midterm scenarios for energy consumption and GHG emission reductions in the transportation sector of the Basque Autonomous Community (Spain). He et al. (2013) estimated the 2030 energy consumption of and GHG emissions from China's urban passenger transportation sector, including cars, taxis, and buses, and analyzed the GHG emission mitigation scenarios based on the transportation mode choices. Ko et al. (2014) examined the scenario-based CO_2 emission reduction potential of passenger vehicles in South Korea. Chen and Lei (2017) used a path analysis model to calculate the direct and indirect influences of driving factors on CO_2 emissions in the Beijing transportation sector and investigated causal relationships between variables. Hickman et al. (2010) developed a simulation model and considered the implementation of a series of potential policy packages in London's transportation sector, including the road, rail, and aviation sub-sectors. Mustapa and Bekhet (2016) investigated effective policy options that can reduce CO_2 emissions in the Malaysian road transportation sector based on a self-developed optimization-based model.

In this study, our goal was to identify the measures for reducing GHG emissions and to analyze emission mitigation potential using the TIMES model. In contrast to previous studies, we considered the transportation sector as a whole, studying not only the road but also the rail, waterborne, and aviation sub-sectors. Therefore, a more comprehensive analysis of the opportunities and implications of pursuing GHG mitigation goals is provided in this study.

3. Methodology

3.1. TIMES model

The TIMES model was developed in 2001 and has become a leading global energy system model. The model is a dynamic partial equilibrium model for calculating the combination of energy technologies and commodity flows that maximizes the total surplus or minimizes the total net cost of energy systems for target countries or regions, with assumptions on the competitive market and perfect foresight over a certain time horizon (Loulou et al., 2016; Vaillancourt et al., 2008). The TIMES model uses a multi-period, deterministic linear programming model. The model is coded in the GAMS language and solved with the CPLEX solver. The mathematical details of the model are described in manuals online (Loulou et al., 2016). A brief description of the basic architecture of the TIMES model is provided in this section based on our previous study (Park et al., 2016).

The model is intended to minimize the discounted total costs in a target energy system over the planning horizon, including the nine following components: annual equivalent capital costs for investing into and demolishing processes; annual fixed and variable operation and maintenance costs; transportation or transaction costs from exogenous imports and domestic mining; delivery costs for commodities spent by processes; commodity flows and process activities or investment-related taxes and subsidies; revenue from exogenous exports; revenue incurred from the recovery of embedded commodities; salvage value of processes; and welfare loss incurred by consumers.

Three basic physical or logical constraint categories are used to indicate the energy system properties. The first category is called the *capacity transfer constraint*. This category represents the relationship of the process capacities over time. In each region and each period, the total available capacities of each process is equal to the sum of the capacities installed in the past and current periods plus the existing capacity at the beginning of the planning horizon. The second category is the *use of capacity constraint*. In this category, the activity of each process should not exceed its available capacity for each region, each period, and each time-slice. The last category is the *commodity balance constraint*. In this category, the sum of the production of each commodity by the processes in a region and the imports from other regions should be balanced with the amount spent in the same region or exported to other regions in the model.

The TIMES model is frequently used to analyze the supply of and demand for energy as well as the effects of GHG emissions at a national- or local-scale within a mid- to long-term time horizon (Vaillancourt et al., 2008). The main outcomes of the TIMES model include activities, emissions, and investments per period with regard to energy technology, as well as implicit prices (i.e., opportunity costs) of energy types and emissions. In the TIMES model, the reduction in GHG emissions is analyzed through fuel substitution and the deployment of best available technologies in the energy sector.

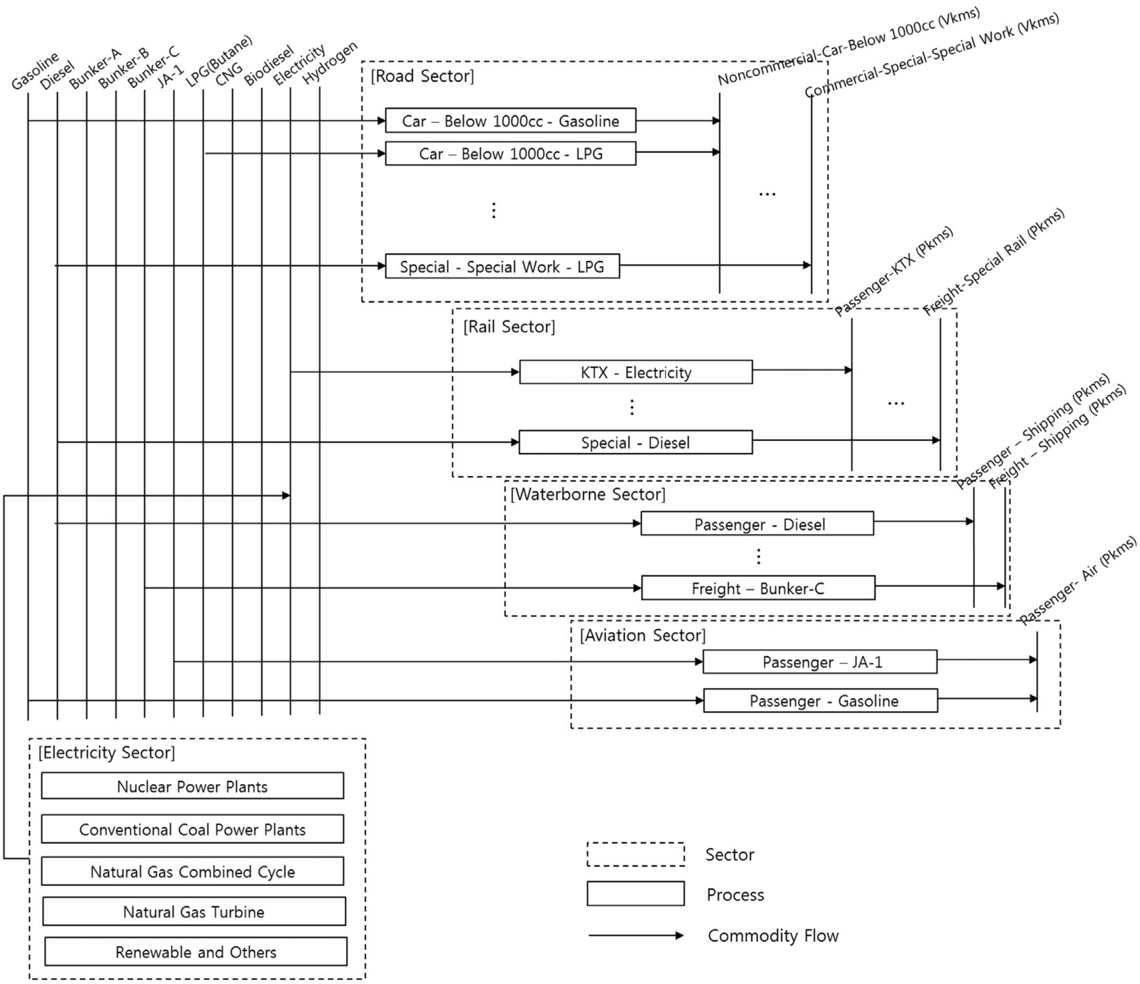

Fig. 2. Schematic of the TIMES model structure.

3.2. Key assumptions and model structure

First, we defined the year 2013 as the base year of the model, because 2013 was the most recent year for which the national statistics related to GHG emission inventory and the energy balance existed and it was also the base year of the model used for the Korean INDC in 2015 (ROK Government, 2016). The analysis time (planning) horizon was set to 2030; therefore, the model was run over an 18-year period in one-year increments. In accordance with the Korean INDC, a global annual discount rate of 3.83%, the Korean Treasury Bond's five-year interest rate in 2014, was applied (ROK Government, 2016). Because of the lack of seasonal and time-dependent data for the transportation sector, we did not consider periods shorter than one year.

We compiled national statistics for the Korean transportation sector from open-access national database systems (KOTEMS; KTDB; KEEI, 2015) and from the database system of the Korea Automobile Manufacturing Association (KAMA). Next we constructed the reference energy system (RES) for our model. The RES consists of several processes and commodities and is divided into four transportation sub-sectors (i.e., road, rail, waterborne, and aviation), a fuel upstream sector, and an electricity sector, as shown in Fig. 2. According to the national statistics, we considered not only the nine fuel types that the Korean transportation sector used in 2013, but also two more fuel types, biodiesel and hydrogen, for future technologies. For these fuel types, excluding electricity, we used the energy densities and country-specific GHG emission factors for the year 2011 as recognized by the Korean government (GIR, 2015; KEEI, 2015). Because the GHG emission factor of electricity can vary with the generation portfolio in the electricity sector, we incorporated the electricity sector into our model and generated its GHG emission factor internally. For the electricity sector, we used a previously well-developed model (Choi et al., 2015) and revised it based on the national basic plan for electricity demand and supply, released by the Ministry of Trade, Industry and Energy (MOTIE) in 2015 (MOTIE, 2015). We used domestic price data for the fuel types and assumed that future prices will follow the U.S. Energy Information Administration's projections (EIA, 2015). Table 1 summarizes the energy densities, GHG emission factors, and prices for all fuel types.

Table 1
Energy density and GHG emission factor for each fuel type.

Fuel	Energy density (HHV) (1 TOE = 107 kcal)	GHG emission factor (t CO_2eq./TOE)	Price in 2013 (2013 M. KRW[a]/TOE)
Gasoline	7780 kcal/L	2.696	2.474
Diesel	9010 kcal/L	2.898	1.920
Bunker-A	9290 kcal/L	3.033	1.292
Bunker-B	9670 kcal/L	3.042	0.940
Bunker-C	9950 kcal/L	3.047	0.940
JA-1 (Jet Fuel)	8730 kcal/L	2.791	1.460
LPG-Butane	11,850 kcal/kg	2.429	1.279
CNG (Compressed Natural Gas)	13,040 kcal/kg	2.122	0.645
Electricity	860 kcal/kWh	5.590–4.780[b] (varies over the planning horizon)	1.320[b]
Biodiesel	8340 kcal/L	0	2.549
Hydrogen	33,890 kcal/kg	0	–[c]

Note:
[a] M. KRW represents million Korean won, which is the monetary unit of South Korea. The USD to KRW exchange rate equals about 1100.
[b] These numbers are calculated from the TIMES model.
[c] The official domestic price of hydrogen fuel and its future projections are not available. In this study, we set the hydrogen fuel price at zero since hydrogen fuel may be obtained as a by-product of industrial chemical processes in the near future.

3.3. Sub-sectoral technological or demand processes under the BAU scenario

We specified four sub-sectors based on several technological or demand processes. The road transportation sub-sector consisted of 52 technological processes by their purpose (e.g., non-commercial vehicle, commercial vehicle), type (car, SUV, bus), class (light-weight, compact, midsize), and fuel type (gasoline, diesel, LPG). Tables 2 and 3 present the processes, number of registered vehicles, average annual travel distances, and purchase prices for 2013. The rail, waterborne, and aviation transportation sub-sectors were specified into the same demand processes owing to a lack of data. The rail, waterborne, and aviation transportation sub-sectors consisted of five, two, and one demand processes, respectively, according to their purposes. Table 4 summarizes the processes, demand data, and energy intensities for 2013.

Table 2
The 24 technological processes of non-business vehicles and the numbers of registered vehicles, average real fuel economy, average annual travel distances, and purchase prices in 2013.

Type	Class	Fuel	Number of registered vehicles	Avg. real fuel economy (km/l)	Avg. annual travel distance (km/vehicle)	Purchase price (2013 M. KRW/vehicle)
Car	Lightweight Car (Below 1000cc)	Gasoline	1,245,618	8.96	9089	9.17
		LPG	192,574	5.79		10.34
	Compact Car (Below 1600cc)	Gasoline	981,118	7.25	8140	16.67
		Diesel	354,961	16.77		18.69
		LPG	206,559	4.98		16.06
	Midsize Car (Below 2000cc)	Gasoline	3,546,384	6.97	11,169	23.81
		Diesel	1,282,879	15.45		26.82
		LPG	746,534	4.74		16.89
	Fullsize Car (Above 2000cc)	Gasoline	1,443,328	6.25	13,286	30.19
		Diesel	522,185	13.00		32.05
		LPG	303,870	3.92		27.24
SUV	Midsize SUV (Below 2000cc)	Gasoline	44,169	5.70	13,779	23.54
		Diesel	2,164,409	12.72		25.67
	Fullsize SUV (Above 2000cc)	Gasoline	29,009	5.92	14,573	30.19
		Diesel	1,421,464	12.96		32.05
Bus	Below 15 passengers	Diesel	812,040	8.20	14,600	22.21
	Below 35 passengers	Diesel	26,221	6.60	16,717	56.57
	Above 36 passengers	Diesel	16,182	3.77	19,272	145.05
Truck	Below 1 ton	Diesel	2,622,147	8.57	14,152	13.00
	Below 5 ton	Diesel	225,334	6.50	16,869	40.83
	Above 5 ton	Diesel	70,660	5.09	18,588	64.01
Special	Towing	Diesel	3862	3.20	31,573	64.01
	Rescue	Diesel	4596	3.20	17,046	64.01
	Special work	Diesel	8969	3.20	11,425	64.01

Table 3
The 28 technological processes of business vehicles and the numbers of registered vehicles, average real fuel economy, average annual travel distances, and purchase prices in 2013.

Type	Class	Fuel	Number of Registered vehicles	Avg. real fuel economy (km/l)	Avg. annual travel distance (km/vehicle)	Purchase price (2013 M. KRW/vehicle)
Car	Lightweight Car (Below 1000cc)	Gasoline	4076	8.96	22,338	9.17
		LPG	4584	5.79		10.34
	Compact Car (Below 1600cc)	Gasoline	988	7.25	27,631	16.67
		Diesel	582	16.77		18.69
		LPG	1513	4.98		16.06
	Midsize Car (Below 2000cc)	Gasoline	70,068	6.97	48,545	23.81
		Diesel	41,235	15.45		26.82
		LPG	306,850	4.74		16.89
	Fullsize Car (Above 2000cc)	Gasoline	19,232	6.25	32,668	30.19
		Diesel	11,318	13.00		32.05
		LPG	84,225	3.92		27.24
SUV	Midsize SUV (Below 2000cc)	Gasoline	652	5.70	24,236	23.54
		Diesel	31,946	12.72		25.67
	Fullsize SUV (Above 2000cc)	Gasoline	319	5.92	26,937	30.19
		Diesel	15,616	12.96		32.05
Bus	City Bus	Diesel	6125	3.77	37,194	95.03
		CNG	25,778	1.90	37,194	117.30
	Intercity Bus	Diesel	23,376	3.77	80,738	143.66
	Chartered Bus	Diesel	40,955	3.77	80,738	143.66
	Express Bus	Diesel	127	6.60	80,738	182.92
	Bus General	Diesel	19,044	6.60	17,484	21.59
	Bus Special	Diesel	957	8.57	17,484	21.59
Truck	Below 1 ton	Diesel	89,341	6.50	31,901	13.00
	Below 5 ton	Diesel	198,704	5.09	45,881	40.83
	Above 5 ton	Diesel	79,521	3.20	70,044	64.01
Special	Towing	Diesel	31,283	3.20	84,680	64.01
	Rescue	Diesel	7185	3.20	25,879	64.01
	Special work	Diesel	10,103	6.60	12,118	64.01

Table 4
The 8 demand processes in the rail, waterborne, and aviation sub-sectors and their demands and energy intensities in 2013.

Sub-sector		Type	Demand (1000 Passenger-km or 1000 Ton-km)	Energy intensity (TOE/ Passenger-km or Ton-km)	Fuel mixture						
					Gasoline	Diesel	Bunker-A	Bunker-B	Bunker-C	JA-1 (Jet Fuel)	Electricity
Rail	Passenger	KTX	14,271,948	0.0032	–	0.0001	–	–	–	–	0.9999
		General Rail	8,137,014	–	–	0.4968	–	–	–	–	0.5032
		Metropolitan Subway	15,905,066	–	–	0.0029	–	–	–	–	0.9971
		Other Subway	27,822,000	–	–	0.0034	–	–	–	–	0.9966
	Freight	Special Rail	10,458,879	–	–	1	–	–	–	–	–
Waterborne	Passenger		1,011,000	0.1289	–	0.7116	0.0713	–	0.2171	–	–
	Freight		30,476,000	0.0113	–	0.3240	0.2120	0.0689	0.3950	–	–
Aviation	Passenger		9,092,997	0.0515	0.0029	–	–	–	–	0.9971	–

3.4. Future demand projections under the BAU scenario

The TIMES model requires exogenously determined projections on demands. In our model, these demands were defined as vehicle-km in the road transportation sub-sector and as passenger-km or ton-km in the other three sub-sectors. As a result, to project how those demands will change over the analysis time horizon under the BAU scenario, we used the most common and simple future projection methods, described below.

First, for the road transportation sub-sector, we considered the demand for technological processes. The projection for each demand was calculated based on the product of the projection on the number of registered vehicles and the average annual travel distance. We projected the number of registered vehicles for each technological process using a log-linear regression model and the most recent 10 years of historical data, similar to the process reported in a previous study (Button et al., 1993). The model uses GDP and population as independent variables, therefore we used forecast data for GDP and population provided by the National Assembly

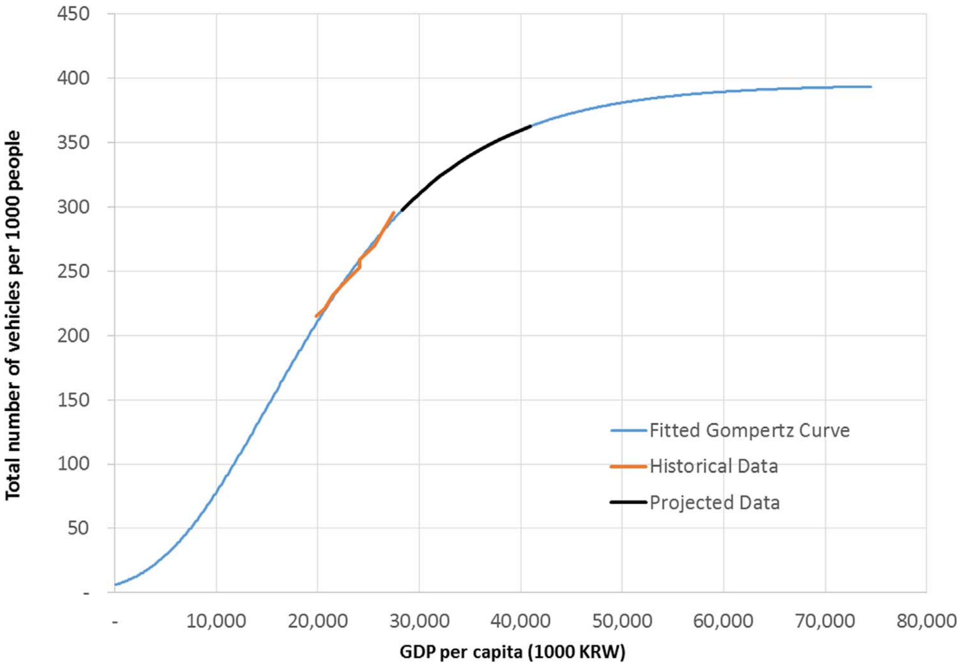

Fig. 3. Vehicle ownership level and GDP per capita (note: The saturation level is set at 395 per 1000 people (Park et al. 2012)).

Budget Office in South Korea (National Assembly Budget Office, 2016). The number of registered non-business vehicles was adjusted to coordinate with the projection of the vehicle ownership level fitted by the Gompertz curve (Dargay and Gately, 1999; Dargay et al., 2007) (Fig. 3). In addition, we projected the average annual travel distance for each technological process based on a simple time-series model: the autoregressive integrated moving average (ARIMA) model.

For the other three sub-sectors, we projected the demand for all demand processes. After comparing the projections based on 3 popular models for the rail and aviation transportation sub-sectors [log-linear regression, ARIMA, and ARIMA with GDP and population time series data as additional explanatory variables (ARIMAX)] and 24 years of historical data (1990–2014), we selected the results of the ARIMAX model (Kulshreshtha et al., 2001; Abed et al., 2001; Profillidis and Botzoris, 2006). Note that we could not consider the model shift effects between the processes within a specific sub-sector or between the sub-sectors because of a lack of data. All projection results are summarized in Appendix A.

3.5. Energy consumption and GHG emission calculations under the BAU scenario

In the TIMES model, with previously defined energy intensities, GHG emission factors, and demands for technological and demand processes in Sections 3.2–3.4, the energy consumption and GHG emissions were calculated as follows:

$$X_{r_1,j,t} = \sum_{i \in I_{r_1}} stock_{i,t} \times FE_{i,t} \times TD_{i,t} \times SE_{i,j,t} \quad \forall\, j,t$$

$$X_{s,j,t} = \sum_{i \in I_s} DE_{i,t} \times EI_{i,t} \times SE_{i,j,t} \quad \forall\, j,t,s \in S\backslash\{r_1\}$$

$$E_{s,t} = \sum_{j \in J_i} X_{s,j,t} \times GHG_j \quad \forall\, t,s \in S$$

where s is the sub-sectors; $s \in S = \{r_1,r_2,m,a\}$, r_1 is the road transportation sub-sector; i is the technological or demand process; I_s is the set of processes in sub-sector s; j is the fuel type; j is the time (year); $X_{s,j,t}$ is the energy consumption of fuel j in sub-sector s; $stock_{i,t}$ is the number of registered vehicles for the technological process i in the road sub-sector; $FE_{i,t}$ is the fuel economy for the technological process i in the road sub-sector; $TD_{i,t}$ is the travel distance for the technological process i in the road sub-sector; $SE_{i,j,t}$ is the share of fuel type j for the technological or demand process i; $DE_{i,t}$ is demand for the demand process i in the rail, waterborne, and aviation sub-sectors; $EI_{i,t}$ is energy intensity for the demand process i in the rail, waterborne, and aviation sub-sectors; $E_{s,t}$ is the amount of GHG emissions from sub-sector s; and GHG_j is the GHG emissions factor for fuel type j.

Under the BAU scenario, we collected the average real fuel economy data and purchase price data for each technological process in the road transportation sub-sector from the Korea Energy Agency (KEMCO) and KAMA, respectively; these data are shown in Tables 2 and 3. We assumed that the future fuel economy will follow the U.S. EIA's projections (EIA, 2015). However, we assumed that the prices are invariant during the analysis period because of a lack of reliable projections. We also assumed that the energy

Table 5
Energy consumptions and GHG emissions from the Korean transportation sector under the BAU scenario.

Sub-sector	Energy/GHG emissions	Type	2013	2017	2020	2025	2030
Road	Energy Consumption (1000 TOE)	Gasoline	16,159	16,764	17,194	17,865	18,484
		Diesel	9261	9562	9765	10,061	10,307
		LPG & CNG	280	288	291	298	305
	GHG Emission (1000 t CO_2eq)	Direct	84,664	87,580	89,614	92,727	96,516
Rail	Energy Consumption (1000 TOE)	Diesel	156	157	156	159	163
		Electricity	390	409	422	483	579
	GHG Emission (1000 t CO_2eq)	Direct	453	456	453	460	472
		Indirect[a]	2078	2181	2250	2577	3086
Waterborne	Energy Consumption (1000 TOE)	Diesel	204	193	183	182	196
		Bunker-A	82	78	76	70	67
		Bunker-B	24	22	21	19	17
		Bunker-C	164	182	197	209	208
	GHG Emission (1000 t CO_2eq)	Direct	1416	1417	1428	1435	1457
Aviation	Energy Consumption (1000 TOE)	JA-1 (Jet Fuel)	467	491	499	605	746
		Gasoline	1	1	1	2	2
	GHG Emission (1000 t CO_2eq)	Direct	1306	1374	1396	1692	2089
Total	GHG Emission (1000 t CO_2eq)	Direct	87,839	90,827	92,891	96,314	100,534
		Indirect[a]	2078	2181	2250	2577	3086

Note:
[a] The indirect GHG emission is caused by electricity consumption.

intensity and the share of each fuel type of each demand process in the rail, waterborne, and aviation transportation sub-sectors stayed constant at the base year's value during the analysis period (Table 4). With these assumptions, the calculated energy consumptions and GHG emissions of the four sub-sectors were determined and are summarized in Table 5.

4. Technology policy options

Based on the new technology policies that the Korean government already adopted or is considering adopting in the near future, six technology policy options for GHG emission reductions in the transportation sector were deduced. Table 6 summarizes these options, and the details of the options are described in the following sub-sections.

4.1. Option 1: Green vehicle diffusion and improved average fuel economy of cars and SUVs

In 2014, the Ministry of Environment announced a new policy stating that the average fuel economy of new cars and SUVs in the road transportation sub-sector should increase from 17 km/L in 2015 to 24.3 km/L in 2020. In this policy, the average fuel economy is calculated using a production-weighted harmonic mean and electric vehicles (EVs) and hydrogen fuel cell vehicles (FCVs) are double counted. Based on this policy, we defined the first option and assumed that the annual growth rate (CAGR) of the average fuel economy of new cars and SUVs is 1% from 2020 to 2030. We further assumed that the average lifetime of cars and SUVs is 14.5 years and the conversion ratio of the average real fuel economies of cars and SUVs to the average official fuel economies of new cars and SUVs is 0.763 based on the historical data.

In addition, according to a national plan released in 2015 (ROK Government, 2015b), we set a scenario on the diffusion of green vehicles (i.e., hybrid EVs, EVs, and FCVs) in the first option (Table 7). We set the fuel economies of the green vehicles in 2015 as

Table 6
Summary of the technology policy options.

Technology policy option	Description
Option 1: Green vehicle diffusion and improved average fuel economy of cars and SUVs	– Improvement in the average fuel economy of cars and SUVs: 17 km/L in 2015 to 24.3 km/L in 2020 and CAGR 1% from 2020 to 2030 – Diffusion of green vehicles: 4 million hybrid EVs, 1 million EVs, and 640,000 FCVs by 2030
Option 2: Improved average fuel economy of buses and trucks	– Improvement of the average fuel economy of buses and trucks: 20% by 2020 and 40% by 2030, relative to 2013
Option 3: Higher biodiesel blend ratio	– BD 2.5 in 2015 to BD 3.0 in 2020
Option 4: Electric city bus diffusion	– Diffusion of electric city buses: 12,300 buses by 2030
Option 5: Improved energy intensity in the waterborne transportation sub-sector	– Improvement in energy intensity: 5% by 2030 relative to 2013 – BD 10 in 2030
Option 6: Improved energy intensity in the aviation transportation sub-sector	– Improvement in energy intensity: 2% by 2030 relative to 2013

Table 7
Scenario of the diffusion of green vehicles.

Unit: Vehicle	2015	2020	2025	2030	Purchase price[a] (2013 M. KRW/vehicle)
Hybrid Electric Vehicle	169,000	868,000	2,400,000	4,000,000	29.3
Electric Vehicle	6000	200,000	580,000	1,000,000	41.0
Hydrogen Fuel Cell Vehicle	80	9000	100,000	640,000	66.9

Note:
[a] Purchase price data do not include subsidies for green vehicles.

18.2 km/L for hybrid EVs, 5 km/kWh (= 41.28 km/L) for EVs, and 76.8 km/kg (= 27.8 km/L) for FCVs, respectively, based on the fuel economies of representative vehicles in the current Korean market, such as the Hyundai Motors Sonata Hybrid. We assumed that their future fuel economies would follow the U.S. EIA's projections (EIA, 2015); therefore, the average annual growth rates are set at 2%, 0.25%, and 0.25% for hybrid EVs, EVs, and FCVs, respectively. We also set the purchase prices of green vehicles based on those of representative vehicles in the Korean market. The same as for conventional vehicles, we assumed that prices are invariant during the analysis period.

4.2. Option 2: Improved average fuel economy of buses and trucks

Even though no specific policy yet exists, we considered the possibility of a future policy on the average fuel economy of new buses and trucks promulgated by the Ministry of Trade, Industry, and Energy and the Ministry of Environment. We defined a second option such that the average fuel economy of all buses and trucks in the road transportation sub-sector should gradually improve (20% by 2025 and 40% by 2040 relative to 2013). We also assumed that the average lifetime of buses and trucks is 9 years and the conversion ratio of the average real fuel economy of buses and trucks to the average fuel economy of new buses and trucks is 0.763 based on historical data.

4.3. Option 3: Higher biodiesel blend ratio

In 2015, South Korea enacted the Renewable Fuel Standard (RFS), which requires that the diesel fuel for the road transportation sub-sector sold in South Korea contain a certain volume of biodiesel. In the RFS, the biodiesel blend ratio increases from 2.5% in 2015 to 3% in 2020 (BD 2.5 in 2015 to BD 3.0 in 2020). Therefore, we defined a third option based on the RFS.

4.4. Option 4: Electric city bus diffusion

The Ministry of Land, Infrastructure, and Transport has funded an R&D program to develop charging infrastructure for electric city buses. The Ministry has a plan to gradually increase the number of electric city buses to 12,300 by 2030; therefore, we defined a fourth option of electric city bus diffusion. We assumed that the fuel economy and the purchase price of electric city buses stay at 0.5 km/kWh and 480 M. KRW per vehicle, respectively, during the analysis period.

4.5. Options 5 and 6: Improved energy intensity in the waterborne and aviation transportation sub-sectors, respectively

Even though no specific policies yet exist, we considered the possibility of future policies on energy intensity improvement in the waterborne and aviation transportation sub-sectors promulgated by MOLIT. A fifth option was defined as: energy intensity in the waterborne transportation sub-sector should gradually increase by 5% by 2030, relative to 2013. In addition, we assumed that the biodiesel blend ratio also increases to 10% in 2030 under the fifth option. The sixth option was defined as: energy intensity in the aviation transportation sub-sector should gradually increase by 2% by 2030, relative to 2013.

5. Results and discussions

5.1. GHG emission mitigation potentials

We defined several new scenarios in which a technology policy option or a combination of options is implemented. Under each scenario, the TIMES model adopted new demand projections and calculated energy consumption and GHG emissions as described in Section 3.5. We then analyzed the mitigation potential of GHG emissions, as the decreased GHG emissions under the new scenarios compared to the BAU scenario.

First, we analyzed the mitigation potential when only one technology policy option is implemented. Table 8 summarizes the analysis results. For Option 1, the net annual GHG emissions mitigation potential was 18.7 Mt CO_2eq in 2030. Because EVs replace some conventional (i.e. gasoline-, diesel-, and LPG-fueled) vehicles, they reduce direct GHG emissions but increase some indirect GHG emissions from electricity consumption. Therefore, the net potential was calculated as the decreased amount of direct GHG emissions minus the increased amount of indirect GHG emissions. In fact, this potential consists of two contributors: the diffusion of

Table 8
GHG emission mitigation potential of each technology policy option.

Unit: 1000 t CO_2eq	2017 Annual	2020 Annual	2025 Annual	2030 Annual	2014–2030 Cumulative
Option 1[a]	4591 (4667–76)	8193 (8517–324)	13,688 (14,598–910)	18,702 (20,218–1515)	174,671 (185,245–10,574)
Option 2	3888	6420	9737	12,176	125,481
Option 3	492	1013	1441	1491	17,814
Option 4[a]	−21 (38–59)	−47 (93–140)	−68 (182–251)	−109 (267–376)	−912 (2185–3097)
Option 5	30	58	97	124	1196
Option 6	2	7	20	35	239

Note:
[a] The values in Options 1 and 4 represent net potentials, the decreased amount of direct GHG emissions minus the increased amount of indirect GHG emissions.

green vehicles and an improved average fuel economy of new, conventional cars and SUVs. Based on the available data, assumptions, and the scenario on the diffusion of green vehicles, the average fuel economy of new conventional cars and SUVs in 2020 was calculated as 18.1 km/L. Therefore, the improved fuel economy of new conventional vehicles contributed 55% of the mitigation potential.

For Option 2, the estimate of the annual GHG emissions mitigation potential in 2030 was 12.2 Mt CO_2eq. The potential is relatively large because the fuel economy of buses and trucks has not yet been regulated. For Option 3, because of the different energy densities of diesel and biodiesel (Table 1), BD 3.0 replaces 2.78% of diesel in the road transportation sub-sector. About 1.5 Mt CO_2eq mitigation potential in 2030 represents the reduction of diesel consumption. For Option 4, the net GHG emission mitigation potential was calculated as −1.1 Mt CO_2eq because it was assumed that electric city buses would replace current CNG-fueled buses. Currently, more than 80% of city buses in South Korea are CNG-fueled, and, therefore, the government's electric city bus diffusion plan will replace both diesel-fueled and CNG-fueled buses. The model results show that the increased amount of indirect GHG emissions was larger than the decreased amount of direct GHG emissions in the replacements, based on the current national basic plan for the electricity generation portfolio. For Option 5, the annual GHG emission mitigation potential in 2030 was estimated as 1.2 Mt CO_2eq. Again, this potential consisted of two contributors: improved energy intensity and fuel replacement from diesel to biodiesel. The former accounts for 60% of the potential. Lastly, the GHG emission mitigation potential of Option 6 was determined to be negligible.

The sum of these potentials over all options does not represent the total GHG emission mitigation potential in the Korean transportation sector from all six technology policy options, as some duplication effects exist between the options. Therefore, we performed a comprehensive analysis to calculate the total GHG emission mitigation potential in the Korean transportation sector. Starting with options 1, 2, 5, and 6, which affect different sub-sectors or technological processes in a sub-sector, and thus, do not have duplication effects, we calculated the potential via step-by-step additions of options 3 and 4. Table 9 summarizes the results of this analysis. The potentials of only options 3 and 4 changed relative to the original results, but those of all other options remained the same.

We conclude that the estimate of total annual GHG emission mitigation potential in 2030 in the Korean transportation sector is 32.0 Mt CO_2eq from all six technology policy options, representing 31% of the total annual GHG emissions in the Korean transportation sector in 2030 under the BAU scenario. Our results show that the contribution of the road transportation sub-sector accounts for 99.5% of the total for the whole transportation sector. Specifically, the contributions of options 1 and 2 represent 59% and 38%, respectively, as illustrated in Fig. 4.

To illustrate the effects of the actual implementation of the technology policy options considered in this study on the future GHG emission mitigation potential of the Korean transportation sector, we performed a sensitivity analysis. Among the six technology

Table 9
Comprehensive analysis results of GHG emission mitigation potentials.

Unit: 1000 t CO_2eq	2017 Annual	2020 Annual	2025 Annual	2030 Annual	2014–2030 Cumulative
Option 1[a]	4,591 (4,667–76)	8,193 (8,517–324)	13,688 (14,598–910)	18,702 (20,218–1,515)	174,671 (185,245–10,574)
Option 2	3,888	6,420	9,737	12,176	125,481
Option 3	445	888	1,051	984	13,646
Option 4[a]	−19 (34–53)	−37 (75–112)	−48 (128–176)	−65 (160–226)	−643 (2165–1522)
Road Transportation Sub-sector Total	8905	15,464	24,428	31,796	313,155
Option 5	30	58	97	124	1196
Option 6	2	7	20	35	239
Total	8937	15,529	24,546	31,955	314,591

[a] Note: The values in Option 1 and Option 4 represent the net value of potentials, the decrease in direct GHG emissions minus the increase in indirect GHG emissions.

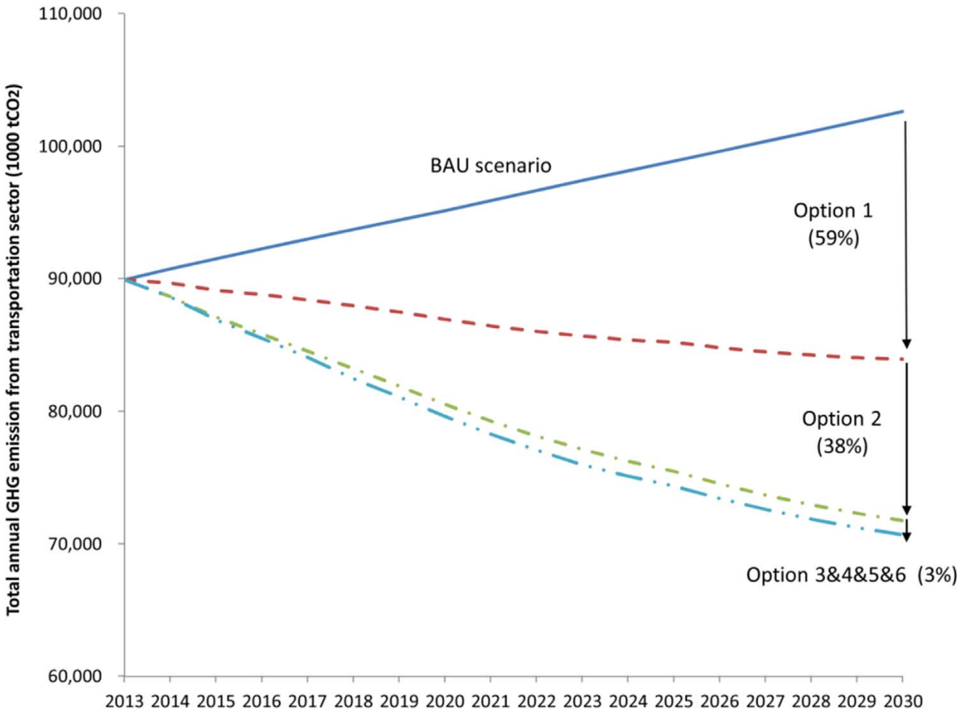

Fig. 4. Comprehensive analysis result of the GHG emission mitigation potential in the Korean transportation sector.

policy options considered in this study, only two were implemented based on the government's explicit regulation or plan. For Option 1, the Korean Government has determined that it will not only regulate improvement in the average fuel economy of cars and SUVs, but also the plan for the diffusion of green vehicles by 2020. After 2020, the technology policy options can be differentiated. In addition, the government is currently implementing option 3. Table 10 summarizes the results of comprehensive GHG emission mitigation potentials when only the current explicitly established policies, i.e., Option 1 by 2020 and Option 3, are implemented. The table shows that the total annual GHG emission mitigation potential in 2030 in the Korean transportation sector will reach only 10.8 Mt CO_2eq if the Korean government does not implement any further GHG emission reduction policies. This potential is only about 33.8% of the total potential that can be achieved from all six technology policy options.

5.2. Marginal mitigation costs

We estimated the net economic costs and benefits of the technology policy options. In addition, with the estimates of GHG emission mitigation potentials calculated in Table 9, we analyzed the marginal mitigation costs for the options and compared the costs among the options. In this study, the marginal mitigation cost was calculated as the net present value of total net economic costs during the analysis period divided by the total GHG emission mitigation potential during the analysis period. To calculate the net economic costs of Option 1, we were able to consider the changes, both in total fuel costs and in total technology costs (i.e., vehicle purchase costs), that were calculated in the TIMES model. On the other hand, for the other options, excluding option 4, we could only consider the changes in total fuel costs, but not the changes in total technology costs because of a lack of reliable data. Because option 4 has a negative net GHG emission mitigation potential, we did not incorporated it into this analysis. Table 11 summarizes the results, and the negative values represent net economic benefits rather than costs.

The analysis results show that Options 3 and 5 have positive mitigation costs because of fuel switching from relatively cheap

Table 10
Sensitivity analysis results of GHG emission mitigation potentials.

Unit: 1000 t CO_2eq	2017 Annual	2020 Annual	2025 Annual	2030 Annual	2014–2030 Cumulative
Option 1[a]	4149 (4225–76)	6982 (7306–324)	6079 (6394–314)	5144 (5449–305)	88,386 (92,320–3934)
Option 3	531	1226	1546	1446	19,202
Road Transportation Sub-sector Total	4680	8208	7625	6590	107,588

[a] Note: The values in Option 1 represent the net value of potentials, the decrease in direct GHG emissions minus the increase in indirect GHG emissions.

Table 11
Marginal mitigation costs of technology policy options in the road transportation sector.

	Changes in total fuel costs (2013 M.KRW) (a)	Changes in total technology costs (2013 M.KRW) (b)	Total net economic costs (2013 M.KRW) (a) + (b)	Marginal mitigation costs (2013 M.KRW/t CO_2eq)
Option 1	−35,137,865	25,633,377	−9,504,487	−0.054
Option 2	−47,938,549	–	−47,938,549	−0.274
Option 3	22,968,181	–	22,968,181	1.683
Road Transportation Sub-sector Total	−60,108,360	25,633,377	−34,474,856	−0.199
Option 5	97,943	–	97,943	0.094
Option 6	−133,513	–	−133,513	−0.928
Total	−60,143,930	25,633,377	−34,510,426	−0.109

gasoline or diesel to relatively expensive biodiesel. In contrast, options 1, 2, and 6 represent savings on total fuel costs via improvements in the average fuel economy of vehicles in the road transportation sub-sector and in the energy intensity in the aviation transportation sub-sector. Moreover, the fuel cost savings were greater than the additional technology costs in Option 1. As a result, the mitigation costs of these three options were negative. Over the entire transportation sector, the mitigation cost of the 5 technology policy options was estimated as −0.109 M.KRW/t CO_2eq. For further socioeconomic analysis, we incorporated the additional social overhead capital (SOC) investments for implementing all the technology policy options, such as the R&D investments for new and improved technologies and the costs for EV charging infrastructure. The Korean government estimates the required additional SOC investments as about 1.7×10^6 M.KRW. By including the investments as costs, our analyzed mitigation cost was modified to −0.104 M.KRW/t CO_2eq. Although in many previous studies, such as those by Kesicki (2012) and Tomascheck (2015), positive marginal mitigation costs in the transportation sector were reported, our results show negative mitigation costs for some options. Of course, for options 2 and 6, the different results might be attributed to the critical limitation that we could not consider changes in total technology costs. However, for Option 1, the marginal mitigation costs were still calculated as negative, even though we were able to consider changes in total technology costs. We concluded that the result is possible because a very aggressive target for the improvement on the average fuel economy of vehicles was set in Option 1.

6. Conclusions

In this study, we evaluated the technology policy options for GHG emission mitigation in the Korean transportation sector that the Korean government has adopted or is considering implementing. The GHG emission mitigation potential of these options was investigated comprehensively using the best-known and most widely used bottom-up energy system model, TIMES. The policy implications of our results are summarized as follows.

First, the Korean transportation sector has significant potential for reducing GHG emissions to contribute to the government's first NDC. More than 30% of GHG emissions can be cut compared to the BAU scenario when only the options we considered in this study are implemented. The other options that were not considered in this study should also be evaluated for their mitigation potential. Moreover, the implementation of options for the improvement in average fuel economy of vehicles in the road transportation sub-sector and in energy intensity in the aviation transportation sub-sector can result in social economic benefits, rather than costs. An analysis of the relationship between the economic benefits/costs and the potentials can be used to determine which options should be implemented or adjusted.

Second, the mitigation potential is weighted excessively towards the road transportation sub-sector. Because the road transportation sub-sector accounts for 95% of the GHG emissions from the Korean transportation sector, the highest portion of the mitigation potential in the entire transportation sector belongs to this sub-sector. Nevertheless, only a 5% contribution from the other three sub-sectors to the GHG emission mitigation potential seems too small. Particularly, even though air transportation demand is expected to grow drastically, so is the share of the GHG emissions from this sub-sector, thus the potential of Option 6 is too low. Hence, the policy makers need to consider additional technology policy options, such as mandating a biofuel blend in jet fuel.

Third, some technology policy options are highly correlated with each other. When some options affect the same processes in a sub-sector, there might be some duplication effects on the GHG emission mitigation potentials of the options. For example, cars and SUVs use less fuel under option 1, and, at the same time, some of them (diesel-fueled cars and SUVs) use less CO_2-containing fuel under Option 3. As a result, the mitigation potential of Option 3 decreases when both options 1 and 3 are implemented together, compared to that when only Option 3 is implemented. Moreover, it is sometimes difficult to analyze the mitigation potential of some options separately. In fact, we originally wanted to consider Option 1 as two separate options: the diffusion of green vehicles and the improvement in the average fuel economy of new cars and SUVs. However, we decided to consider it as a single option because the diffusion of green vehicles significantly affects the average fuel economy of new cars and SUVs.

Lastly, some technology policy options in the transportation sector need to be coordinated with policies in the electricity sector.

We showed that Option 4 has a negative GHG emission mitigation potential, since the increased amount of indirect GHG emissions is larger than the decreased amount of direct GHG emissions. From a GHG emission mitigation perspective, this is not be a good policy option. Nevertheless, the Korean government believes that option 4 will help to reduce air pollution, particularly PM_{10} and $PM_{2.5}$, and thus is pursuing this policy option. Based on our analysis results, Option 4 has a trade-off effect between mitigating GHG emissions and mitigating air pollution. However, if the electricity sector adopts a greater number of renewable energy or carbon capture technologies so that the GHG emissions factor of electricity decreases, then the situation may change.

There are some limitations, not only on the use of the model, but also on the use of the analysis results. During model construction, because of a lack of reliable data, we made many assumptions that weakened the optimization-based energy system model. Moreover, we could not specify the technological or demand processes sufficiently in some parts of the analysis. In addition, the results cannot be used directly for the development of a national plan for climate change. During the process of combining the results for all sectors based on the bottom-up approach, some stakeholders intentionally adjusted the GHG emission mitigation potential in the transportation sector. Nevertheless, this study has two important implications. First, it provides policy makers with an easily understandable tool and key reference data to analyze the potential for GHG gas emissions mitigation from the Korean transportation sector. Second, this study emphasizes the practicality of quantitative analysis. The Korean Government needs to prepare and submit NDCs every five years, so future research efforts can work to overcome these limitations.

Acknowledgements

This research was supported by a project, “A revision of the masterplan on sustainable transport logistic development”, funded by the Korea Ministry of Land, Infrastructure, and Transport, and also by the Climate Change Correspondence R&D Program (2014001300003), funded by the Korea Ministry of Environment.

Appendix A

See Tables A.1–A.3.

Table A.1
Projections on the numbers of registered vehicles for 24 technological processes of non-business vehicles under the BAU scenario.

Type	Class	Fuel	2017	2020	2025	2030
Car	Lightweight Car (Below 1000cc)	Gasoline	1,638,189	1,789,124	2,093,988	2,268,018
		LPG	55,997	64,917	88,929	107,613
	Compact Car (Below 1600cc)	Gasoline	1,224,905	1,011,241	727,315	581,659
		Diesel	99,607	86,772	71,695	64,084
		LPG	31,926	43,729	61,164	76,669
	Midsize Car (Below 2000cc)	Gasoline	4,829,638	4,938,988	5,270,760	5,455,474
		Diesel	580,000	566,512	530,205	491,645
		LPG	512,689	533,235	432,493	319,333
	Fullsize Car (Above 2000cc)	Gasoline	2,219,442	2,463,705	2,896,600	3,105,355
		Diesel	612,957	626,136	670,241	696,962
		LPG	273,151	301,573	353,156	369,759
SUV	Midsize SUV (Below 2000cc)	Gasoline	522	549	594	639
		Diesel	164,652	190,755	252,278	294,946
	Fullsize SUV (Above 2000cc)	Gasoline	1,846,207	2,087,591	2,794,299	3,426,505
		Diesel	12,032	11,561	10,849	10,331
Bus	Below 15 passengers	Diesel	1,057,310	1,026,621	987,474	950,861
	Below 35 passengers	Diesel	122	129	139	150
	Above 36 passengers	Diesel	597,315	455,180	257,912	130,733
Truck	Below 1 ton	Diesel	26,477	26,552	26,878	27,193
	Below 5 ton	Diesel	15,410	15,246	14,859	14,567
	Above 5 ton	Diesel	2,605,489	2,619,381	2,675,154	2,728,140
Special	Towing	Diesel	225,934	225,538	235,322	247,747
	Rescue	Diesel	74,315	76,161	80,802	84,594
	Special work	Diesel	4485	4929	5782	6368

Table A.2
Projections on the numbers of registered vehicles for 28 technological processes of business vehicles under the BAU scenario.

Type	Class	Fuel	2017	2020	2025	2030
Car	Lightweight Car (Below 1000cc)	Gasoline	4252	4384	4603	4823
		LPG	4781	4930	5177	5424
	Compact Car (Below 1600cc)	Gasoline	1031	1063	1116	1169
		Diesel	607	625	657	688
		LPG	1579	1628	1709	1791
	Midsize Car (Below 2000cc)	Gasoline	73,089	75,355	79,131	82,907
		Diesel	43,013	44,346	46,568	48,791
		LPG	320,080	330,003	346,540	363,078
	Fullsize Car (Above 2000cc)	Gasoline	20,062	20,684	21,720	22,757
		Diesel	11,806	12,172	12,782	13,392
		LPG	87,856	90,580	95,119	99,659
SUV	Midsize SUV (Below 2000cc)	Gasoline	680	701	736	771
		Diesel	33,323	34,356	36,078	37,800
	Fullsize SUV (Above 2000cc)	Gasoline	332	343	360	377
		Diesel	16,290	16,795	17,636	18,478
Bus	City Bus	Diesel	6389	6587	6918	7248
		CNG	26,889	27,723	29,112	30,501
	Intercity Bus	Diesel	24,384	25,140	26,399	27,659
	Chartered Bus	Diesel	42,721	44,045	46,253	48,460
	Express Bus	Diesel	132	136	143	150
	Bus General	Diesel	19,865	20,481	21,508	22,534
	Bus Special	Diesel	998	1029	1081	1132
Truck	Below 1 ton	Diesel	83,452	80,914	76,035	72,807
	Below 5 ton	Diesel	152,325	159,010	171,839	180,632
	Above 5 ton	Diesel	82,782	84,746	90,052	94,553
Special	Towing	Diesel	30,136	30,475	31,284	31,916
	Rescue	Diesel	7071	7027	7070	7164
	Special work	Diesel	41,044	87,101	145,139	130,092

Table A.3
Projections on the demands for demand processes in the rail, waterborne, and aviation transportation sub-sectors under the BAU scenario.

Sub-sector	Type		Demand (1000 Passenger-km or 1000 Ton-km)			
			2017	2020	2025	2030
Rail	Passenger	KTX	16,980,634	18,556,442	32,689,029	58,316,674
		General Rail	8,200,184	8,149,362	8,265,098	8,463,988
		Metropolitan Subway	16,635,026	17,481,430	17,818,103	17,377,029
		Other Subway	29,457,536	30,225,989	36,479,930	44,370,403
	Freight	Special Rail	9,912,090	9,594,075	10,402,203	11,798,418
Waterborne	Passenger		1,113,000	1,139,000	1,139,000	1,699,000
	Freight		29,291,000	29,282,000	29,282,000	23,772,000
Aviation	Passenger		9,565,169	9,719,278	9,719,278	14,541,302

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